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EPISODIC RIFTING AND VOLCANISM AT KRAFLA IN NORTH ICELAND: RADON (222) EMISSION FROM FUMAROLES NEAR LEIRHNJUKUR

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Abstract. From June 1978 until late 1980 radon emission from the Leirhnjukur fumaroles was monitored within the Krafla caldera of north Iceland where episodic volcanism is occurring. Frequent sampling of the fumaroles shows that no easily identifiable short-term radon precursors occur in the days prior to subsidence of the caldera, despite an observed increase in microseismicity preceding deflation. Following the onset of subsidence, however, the radon emission of the fumaroles gradually increases and reaches a maximum 3-6 days later. The radon in the fumaroles is assumed to be transported from depth by steam and noncondensing gases that slowly escape from the geothermal water table. The cause of the co-episodic increase in radon emission appears to be a temporal rise of the water table driven by fissure closure resulting in an abbreviated transport time for radon to the surface fumaroles. Furthermore, the closing of the fissures appears to cause a transient increase in the velocity of transport, making the shape of the anomalies broader and higher than is predicted from a change in the water level alone. Changes in radon emission also coincide with fluctuations in fumarolic activity and permanent changes in the level of geothermal water that occur during periods of uplift.

Introduction

Krafla volcano in north Iceland is an ideal site for studying the processes of rifting and associated volcanism (Figure 1). Since December 1975, episodes of magma migration and volcanic eruptions have occurred within the Krafla caldera and the north-trending fissure swarm, which marks the plate boundary between the American and the Eurasian plates [Saemundsson, 1974, 1978; Bjornsson et al., 1979]. This paper presents radon data that were collected from fumaroles near Leirhnjukur within the Krafla caldera. The fumaroles emit dry steam and noncondensing gases and are aligned along the current zone of rifting (Figure 2). Both seismic and geodetic techniques have been used to locate a magma chamber in the depth interval between 3 and 7 km below the floor of the Krafla caldera [Einarsson, 1978; Tryggvason, 1980]. A steady flow of magma into the chamber causes a gradual uplift of the caldera floor, and intermittent episodes of rapid subsidence of the caldera floor are associated with rifting and volcanism.

Monitoring of the radon emission from the fumaroles near Leirhnjukur was carried out to search for possible changes in radon emission that might precede the onset of rifting or volcanism by weeks or days. Such radon anomalies could be related to (1) degassing of the magma, (2) deformation of the caldera floor, or (3) changes in the local geothermal reservoir. If intermittent subsurface degassing of magma does take place just before subsidence episodes, it is likely to influence the chemical properties and possibly the radon content of the fumaroles. The deformation of the caldera floor consists of aseismic opening of large cracks in the caldera floor and microseismicity within the crust mainly at depths between 0 and 3 km. Changes in radon emission were expected to correlate with this microseismicity, because variations in the radon content of groundwater have been demonstrated to be an important precursor to some earthquakes [e.g., Wakita, 1978; Asimov et al., 1979; Hauksson, 1981]. In addition, variations in land elevation, geothermal water level, fissure displacement, and fumarolic activity that are observed during uplift or subsidence could induce changes in the geothermal reservoir and affect the radon emission.

The radon data presented in this report cover several small and five major subsidence episodes which occurred in July 1978, November 1978, May 1979, March 1980, and October 1980. The first three events are of similar magnitude in terms of magma volume, elevation change (0.6-0.8 m), and seismic activity. They also are related to repeated rifting of the same portion of the fissure swarm extending north from the rim of the caldera out to approximately 30 km. In early December 1979 and February 1980, two minor slow subsidence episodes resulted in elevation changes of 5 and 10 cm, respectively. Both episodes are associated with earthquake activity and movements of fissures south of the caldera. The episode of March 1980 affected a 20 km long segment of the fissure swarm centered in the Krafla caldera. It resulted in an eruption north of the caldera rim along at least eight different vents. The episode of October 1980 also resulted in a fissure eruption extending from Leirhnjukur approximately 10 km to the north.

Several investigators have studied radon emission from fumaroles or hot springs located close to active volcanos. Iwasaki et al. [1968, 1975] monitored the radon emission at the Oowakidani geothermal area at Hakone volcano in Japan during the time period from 1951 to 1974 and observed two distinctive decreases in radon content that coincided in time with local earthquake swarms. Chirkov [1975] studied the radon content in the gas phase from the hot springs at the base of the Karymsky volcano in Kamchatka from 1966 through 1971. He reported significant correlations between changes in radon emission and eruptive activity. A large increase in radon emission occurred prior to and during a new period of eruptions in 1971. Gasparini and Mantovani [1978], in an attempt to explain the results of Chirkov [1975], suggested that the radon is

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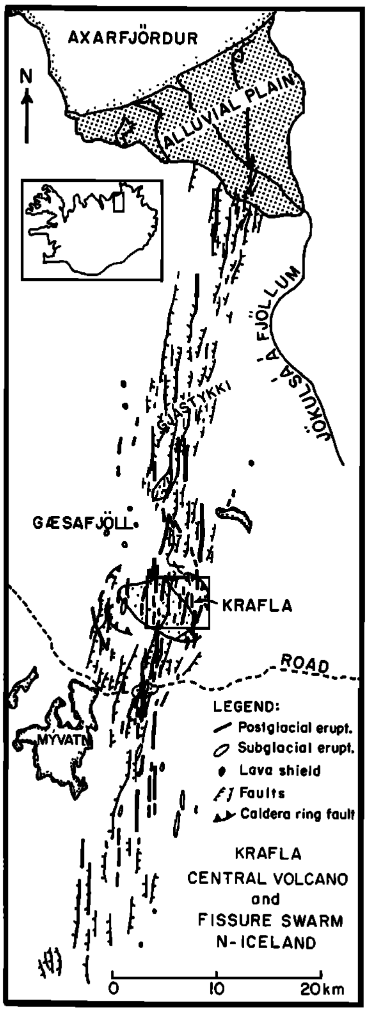

Fig. 1. Krafla central volcano and associated fissure swarm, north Iceland, adapted from Saemundsson [1977, 1978]. The square in the middle of Krafla caldera is shown enlarged in Figure 2.

removed from stationary pore fluids and transported up to the hot springs from depth by flushing of gases through the pore fluids. The flow of these gases is in turn related to the subsurface movement of magma.

At Krafla volcano in north Iceland, Oskarsson [1978] reported changes in the composition of fumarolic gases (H_2 and H_2S decreasedand CO_2 increased) at the initiation of the current activity in December 1975. In addition, he found a correlation between H_2 emission and the ongoing episodic rifting and volcanism. Some of his samples and the samples for radon analysis that are presented in this paper were collected from fumarolic vents in the same area.

Observations and Experimental Procedures

The main purpose of this report is to present radon data collected from June 1978 until the end of 1980 from the fumaroles near Leirhnjukur in the Krafla caldera. Several other relevant data sets are included to aid in interpreting the origin of the radon.

It is noteworthy that this study was carried out in an environment that is very different from what is usually encountered in most studies of radon content as an earthquake precursor. Those studies utilize cold groundwater or warm springs and sample the water phase directly. In this study, the water table (as measured in well KG5; see Figure 3) is inaccessible, and samples are taken only from surface fumaroles.

Radon content. The samples were collected from the vents 'RADON' (in Figure 2) that emit dry steam and noncondensing gases through a surface layer of water-saturated clay. The clay originates from hydrothermal alteration of the hyaloclastite surface rocks. The temperature of the steam is approximately the boiling temperature of water at the pressure of one atmosphere. The temperature at shallow depth (less than 0.5 m) in the clay was measured occasionally and was found to be determined by the temperature of the escaping steam.

During sampling, a 500-cc glass bottle is filled with salt-saturated (NaCl) water and then inverted, allowing the gas phase to displace the salt solution from the bottle. The measured radon content in each sample (as plotted in Figures 3 and 5) is normalized per liter gas, which consists mainly of carbon dioxide and trace amounts of other gases. The sampling frequency varied from every 2 days during periods of expected tectonic activity to biweekly during the less active periods of uplift. If significant changes in fumarolic activity occurred, such as in September 1978 and February 1979, additional samples were collected at shorter time intervals.

During the summer of 1977, several samples were collected from well KG8 for radon analysis (Figure 2) to determine the radon content of the geothermal water at depth.

In the laboratory the radon was stripped from the water and/or gas sample by using helium as a carrier gas and adsorbed onto activated charcoal

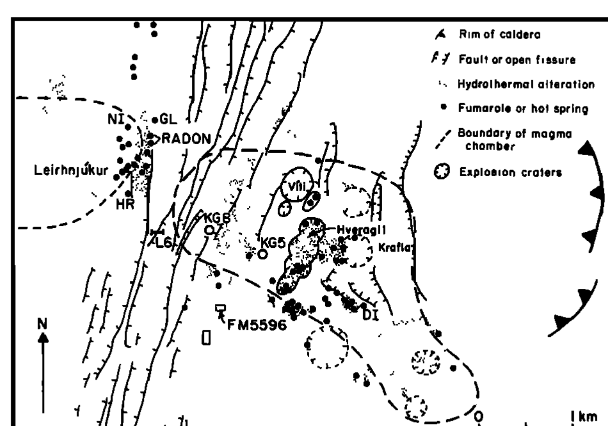

Fig. 2. Detailed map of the Krafla caldera (adapted from Gislason et al. [1978]), showing locations of radon sampling sites, RADON; displacement meter, L6; measurements of groundwater level in well, HG5; a few radon samples were collected from well, KG8; reference benchmark for land elevation, FM5596. The activity of the fumaroles HR, NI, and GL is shown in Figure 4.

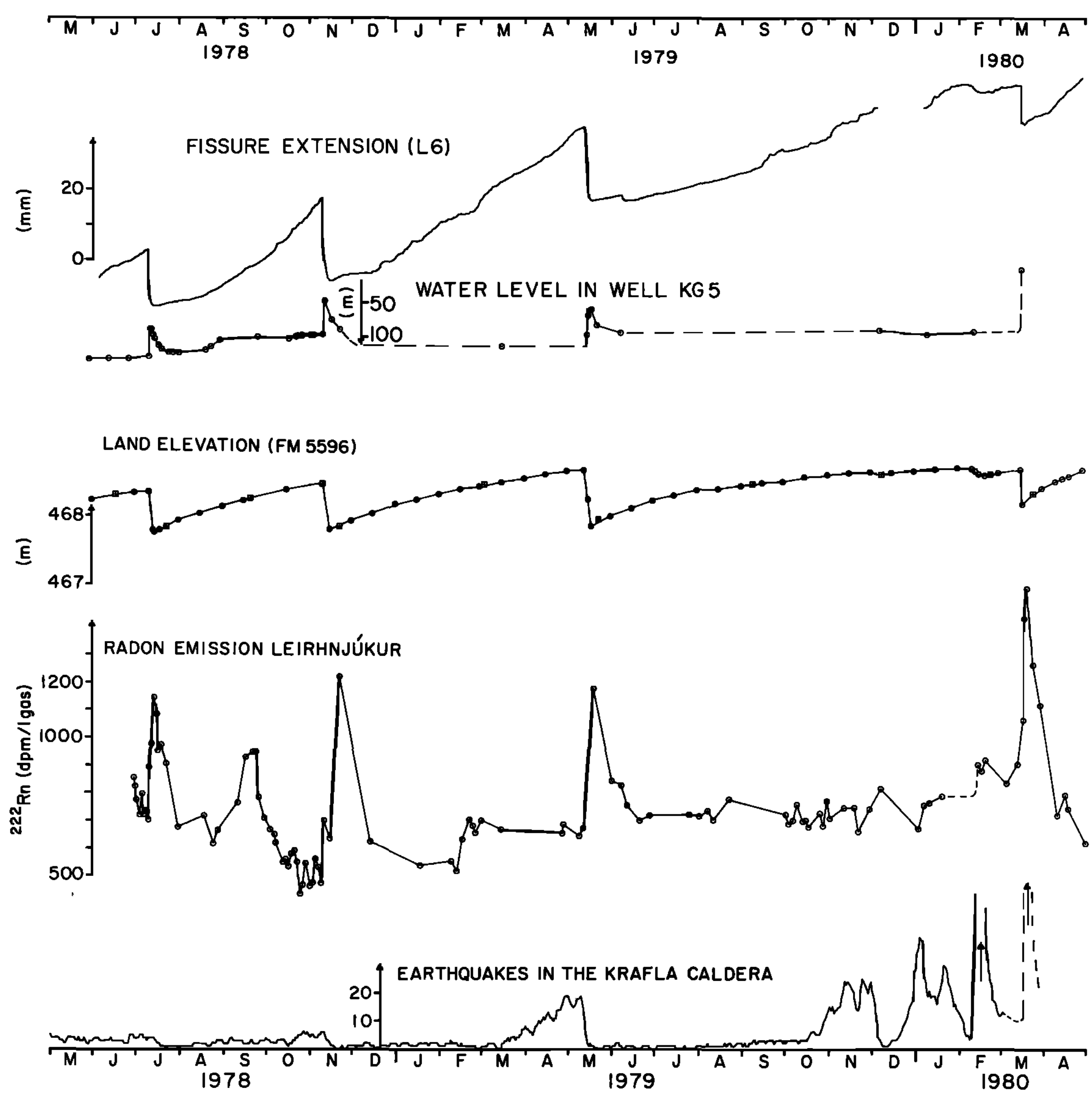

Fig. 3. Time series of data collected at locations shown in Figure 2, from bottom to top: 5-day running mean of earthquakes in the Krafla caldera (P. Einarsson, personal communication, 1980). Radon emission from the fumaroles near Leirhnjukur. Land elevation at benchmark FM5596 (A. Bjornsson, personal communication, 1980). Geothermal water level in well KG5 (V. Stefansson and E. Sigurdsson, personal communication, 1980). Fissure extension measured continuously across an open fissure in the Krafla caldera at site L6.

at -60°C. The charcoal column was evacuated at both -60°C and room temperature to remove impurities and then heated to 470°C. Helium was then used to sweep the liberated radon into an evacuated counting cell (lucas cell), and the cell was placed against a photomultiplier tube in a light-tight chamber for counting. All efficiencies were routinely determined by extracting radon from a standard solution of parent radium-226. Circulation blanks were periodically run on the extraction-transfer system to check against radium-226 contamination. The analytical accuracy of the method was about 3%.

Gas composition. During July 1978 the composition of the gas phase in each radon sample was determined by ORSAT analysis. The results of these analyses indicated that the composition of the gas phase remained essentially constant throughout the month, although a subsidence episode occurred during July 10-12. The main components of the gas phase are approximately 95 vol % (CO_2 + H_2S), 2.5 vol % H_2, and 1.5 vol % (N_2 + inert gases). Since in all the samples the O_2 content was found to be less than 1.0 vol %, the possibility of air contamination is considered to be negligible.

Seismicity. In Figure 3 a 5-day running mean value of the number of earthquakes that occurred in the Krafla caldera from June 1978 to April 1980 is shown. The locations and calculations of magnitudes are those of the Science Institute, University of Iceland (P. Einarsson, personal communication , 1980). The seismicity associated with rifting in the fissure swarm is not included in Figure 3, except when rifting occurred within the Krafla caldera such as in February and March 1980. The largest earthquake that was recorded during this time period had a magnitude of 3.7. It occurred on January 3, 1980 (B. Brandsdottir, personal communication, 1980) and is located about 4 km southwest of the fumaroles used for radon sampling.

Land elevation. The changes in elevation of benchmark FM-5596 (located close to the apex of the uplift) from October 1975 until February 1978 is presented by Bjornsson et al. [1979]. The curve shown in Figure 3 (A. Bjornsson, personal communication, 1980) is the continuation of their previous curve. Data points designated by squares are obtained from leveling surveys that are referenced to a benchmark at the southwest corner of Lake Myvatn. The leveling surveys show that the shape of the inflated bulge has remained fairly constant [Bjornsson et al., 1979]. The filled circles are data points obtained from a short baseline water tube tiltmeter located 1.3 km from the apex of the bulge [Tryggvason, 1980].

Water level. The geothermal water level in the geothermal well KG5 (code established by the National Energy Authority of Iceland) is plotted in Figure 3. The well is located about 2 km southeast of the site where the radon samples were collected (Figure 2). The water level data are from the National Energy Authority of Iceland (V. Stefansson, personal communication, 1980) and the Krafla Power Plant Company (E. Sigurdsson, personal communication, 1980). The data points that are plotted as open circles were obtained by lowering a cable with a galvanic cell down into the well. The uncertainty in these measurements is about ± 2 m. Since well KG5 is the only well within the Krafla caldera where water level is monitored regularly, it is assumed in this report that similar changes in the level of geothermal water occurred below the radon sampling site at Leirhnjukur.

Movements of fissures. Figure 3 also includes a continuous record from a displacement meter whose location is shown in Figure 2. The meter is installed across an open fissure and records displacement with a resolution of 1/10 mm [Hauksson et al., 1979].

Fumarolic activity. The changes in the fumarolic activity are shown schematically in Figure 4 (observations collected by H. Tryggvason (personal communication, 1980)). Significant changes in the steam and gas emission occurred in the fumaroles, steam vents, and hot springs situated near Leirhnjukur. The changes in the fumarolic activity consist of gradually decaying activity in and around the fumarole HR and gradually increasing activity around NE and GL (see Figures 2 and 4). In September 1978 and February 1979 the fumarole GL passes through periods of forceful activity. After the subsidence and the accompanying surface eruption in March 1980, several new fumarolic vents formed northwest of the fumaroles NI and GL.

Results

The most noticeable features of the radon data in Figure 3 consist of (1) the four distinctive peaks that coincide with the episodes of subsidence, (2) the two changes related to variations in fumarolic activity, and (3) a baseline shift that occurred during the May 1979 subsidence episode.

Although the radon data correlate well with the ongoing sequence of uplift and subsidence, the radon data show no obvious correlation between changes in the radon emission and the seismicity (Figure 3). During the periods of uplift, the radon data are characterized by a lack of a secular trend and a good correlation with changes in water level and fumarolic activity. The secular trend can be seen most clearly in the fissure extension data (Figure 3). During the episodes of subsidence similar rador anomalies are observed for the two typical kinds of magma movement, rifting at subsurface migration and surface eruption.

Interpretation

If the radon content of the fumaroles is presumed to originate from the geothermal water table at depth and to be carried to the surface by the escaping steam, the radon data can be interpreted by using other data from the Krafla area.

Radon emission during uplift. The lack of a secular trend in the radon data during periods of uplift suggests that both the length of the transport path and the transport velocity remain constant. The constant depth to the geothermal water table confirms that the length of the transport path is unchanged (Figure 3). The transport velocity depends on the local temperature gradient, which in turn controls the activity of the fumaroles. The activity of the

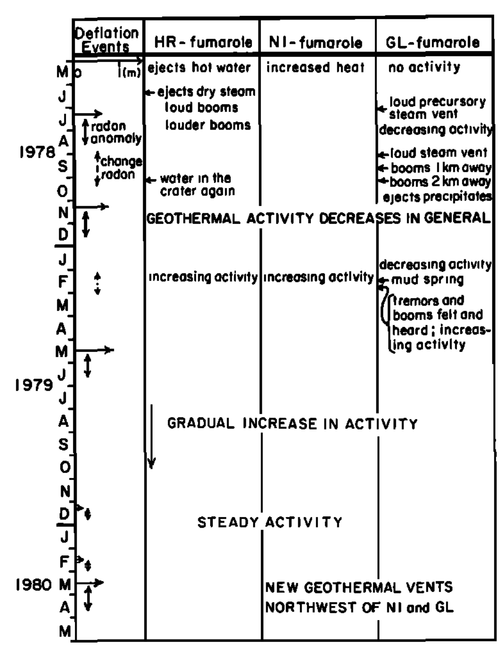

Fig. 4. Changes in fumarolic activity at sites HR, NI, and GL as observed by H. Tryggvason (personal communication, 1980). Note decreasing activity near HR and episodic bursts in activity near GL. Subsidence episodes or deflation events and radon anomalies are shown on left.

fumaroles is influenced also by the secular opening of fissures. The gradual increase in fumarolic activity and the steady radon emission, which coincide with the secular fissure opening, suggest that the flux of steam emission increases but the velocity of transport stays unchanged. Thus the available data (Figure 3) suggest that no substantial changes in the shallow geothermal gradient near Leirhnjukur have occurred since 1978 until late 1980.

Although the gradual increase in fumarolic activity that is observed during the uplift does not affect the radon emission, violent bursts in fumarolic activity can change the radon emission. For instance, two growth and decay episodes of the activity of the GL fumarole, which is located within 100 m distance of the radon sampling site, correlate in time with the changes in radon emission of September 1978 and February 1979 (Figure 4). These episodes might be indicative of small fingering intrusions or dikelets that represent leaks of small quantities of magma away from the chamber. Sudden opening of subsurface cracks and subsequent mixing of aquifer fluids appears to be a less likely explanation than intrusive activity, especially since the resulting thermal output is substantial. The observed radon anomalies indicate a significant increase in the transport velocity of steam from the water table at depth to the fumaroles.

Radon emission during subsidence. The transition from an uplift period to a subsidence episode usually takes place in a few hours. In most cases the simultaneous onset of continuous volcanic tremor and sign reversal of the rate of tilting defines the beginning of a subsidence episode [Bjornsson et al., 1979]. Since early 1978, every subsidence episode for which samples were collected is followed by co-episodic, anomalous radon emission from the fumaroles near Leirhnjukur (Figure 3). The temporal shape (amplitude and time duration) of the co-episodic anomalies is very similar in all cases and therefore suggests a similar mechanism. Intensive sampling was carried out in July 1978 and March 1980 to establish the detailed shape of these anomalies. The July 1978 episode that consisted of a subsurface migration of magma lasted for 2 days and resulted in an 80% increase in radon emission that peaked after 3 days. The March 1980 episode that resulted in a surface eruption north of the fumaroles, on the other hand, lasted only for 12 hours and caused a similarly shaped anomaly (Figure 5). The July 1978 episode was followed by two similar episodes in November 1978 and May 1979. The March 1980 episode was also followed by two similar episodes in July 1980 and October 1980. Since all of these episodes cause almost identical radon anomalies, the two different kinds of magma movement appear to perturb the geothermal reservoir in a similar way.

A further illustration of the relationship between the water level and the radon data is observed during the subsidence episode of May 1979, when the geothermal water table was permanently offset by approximately 20 m. The background radon emission is significantly higher after the episode than before it, thus substantiating the close linkage between the water table elevation and the radon emission. Stefansson [1980] suggested that the raising of the water table is related to small intrusions at shallow crustal depths close to Hveragil (Figure 2), since one of the deep geothermal wells in the Krafla field was plugged by fresh lava during the episode.

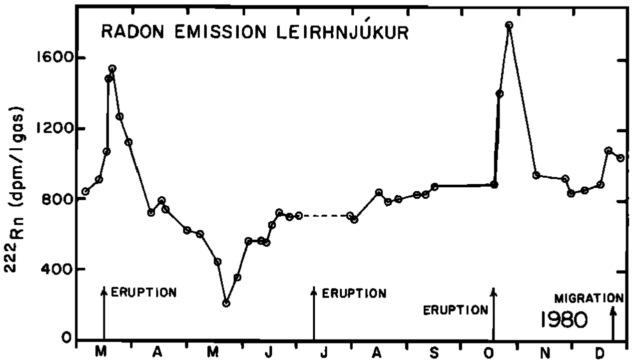

Fig. 5. Radon emission from fumaroles near Leirhnjukur during 1980. No data were collected in July 1980.

Radon Emission During July 1978 Subsidence: A Model

During July 1978, samples were collected daily from the fumaroles near Leirhnjukur and analyzed for radon as well as for gas composition (Figure 6). A subsidence episode that occurred between July 10 and 12, 1978 offers a unique opportunity to establish the cause of the observed radon anomalies.

A simple model of D'Amore and Sabroux [1977], which accounts for the transport of radon in a geothermal reservoir, can be used to determine if perturbations in the convective flow of steam (from the geothermal water table to the fumaroles) are sufficient to cause the radon anomalies. This model uses the initial velocity of steam transport, the radon content of the geothermal water at depth, and the measured changes in water level to predict the radon content of the fumaroles. Then, in turn, the calculated and the observed radon content of the fumaroles are compared to test if changes in other parameters as well as water level are needed to explain the observed radon anomalies.

The model assumes that the rate of change in the radon content N at a location z is equal to the sum of the rate of transport and the rate of decay of the radon content. A differential equation that describes the model can be written as

$$\frac{\partial N}{\partial t} = -V\frac{\partial N}{\partial z} - \lambda N \qquad (1)$$

where V is the velocity of the transport, λ is the decay constant of radon (Rn^{222}), and z is in this case the distance measured from the geothermal water table up to the surface.

The radon content of the geothermal water (214 dpm/kg H_2O) was determined independently from samples collected from the geothermal well KG8, which is located 500 m west-northwest of well KG5. Then assuming a temperature of

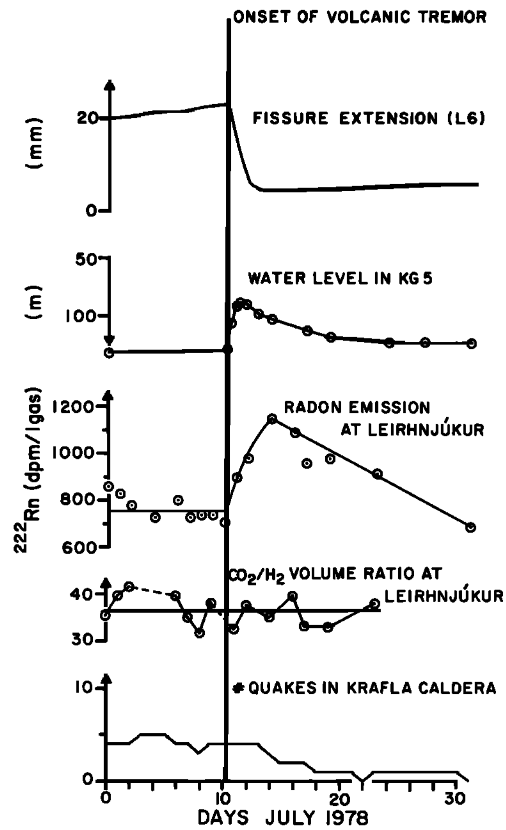

Fig. 6. Detailed data collected during July 1978. The vertical line defines time of onset of volcanic tremor, which signals beginning of subsidence. From bottom to top: 5-day running mean of earthquakes in the Krafla caldera (P. Einarsson, personal communication, 1980). Volume ratio of CO_2/H_2 in the radon samples. Radon emission from fumaroles near Leirhnjukur. Geothermal water level in well KG5 (V. Stefansson, personal communication, 1980). Fissure extension measured at site L6.

approximately 110°C [Stefansson, 1980] and using Henry's law, the radon content of the steam phase at the water interface is found to be N_0 = 1825 dpm/lgas. Integrating equation (1) and assuming that V is independent of depth and z = 0 and N = N_0 at the interface between the steam phase and the water table gives for steady state (dN/dt = 0) the following solution

$$N = N_0 \exp(-\lambda z/V) \qquad (2)$$

Equation (2) indicates that for values of N, N_0, and z obtained during uplift periods, it is possible to estimate the velocity of transport, V = 26 m/d. Then using that velocity value (26 m/d), N_0, and measured values of the depth to the water table (z), the expected change in radon content during the subsidence episode is calculated (Figure 7, below). The calculated radon emission constitutes a reasonable first-order approximation to the observed radon emission (Figure 6, middle), with the exceptions that the observed radon emission shows an earlier and larger increase than the calculated one. To account for this difference, it is necessary to invoke hydrodynamic dispersion or variable transport velocity from the water table up to the fumaroles. The calculated velocity of transport (Figure 7, above) is obtained by using the known N_0, and measured values of N and z. This change in the velocity of transport is expected because closing of the fissures or a sudden narrowing of the flow channel will lead to a transient increase in the velocity. An alternate way of describing the early onset would be to invoke hydrodynamic dispersion that is likely to affect the transport of radon such as to disperse the shape of the calculated radon emission.

Although the model assumes that the radon content of the geothermal water stays constant during the subsidence episode, there are, nonetheless, several possible ways of changing the radon content of the water. The deformation of the caldera floor or the straining of the rock matrix of the aquifer can cause anomalous radon release. Leaks of magmatic gases away from the magma chamber and through the geothermal system can possibly affect the radon content. The second major assumption of the model consists of neglecting the radon emission from the crack walls into the steam phase. The validity of this assumption is partly substantiated by the work of D'Amore et al. [1979] who suggest that the density of steam is not high enough for efficient extraction of radon. The third assumption implicit in equation (1) says that the flow of steam is constrained to a closed channel (i.e., pipe) rather than occurring as diffuse flow through porous media. Using pipe flow appears to be reasonable, since the terrain near the fumaroles is extensively fractured by faults and open fissures. Furthermore, the model implicitly assumes that the temperature of degassing of the geothermal water stays almost constant. This assumption is warranted, since the CO_2/H_2 volume ratio remains almost constant (Figure 6) before and during the subsidence episode, indicating a constant temperature of degassing [D'Amore and Panichi, 1980].

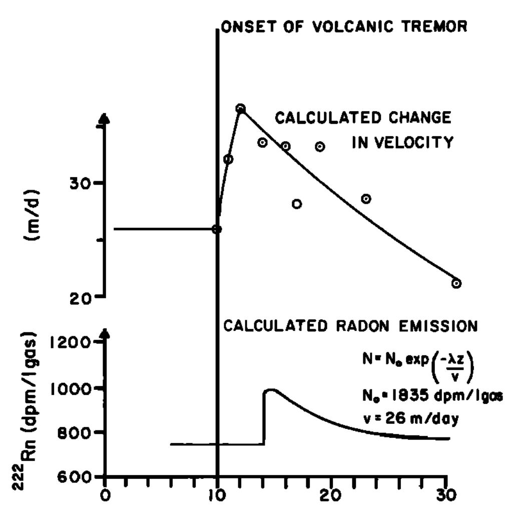

Fig. 7. Results of model calculations. (below) Calculated radon emission; (above) calculated change in velocity of radon transport up from water table to fumaroles.

Discussion

The initial purpose of this study was to look for possible precursory radon anomalies that could be associated with (1) degassing of the magma at depth, (2) deformation of the caldera floor, or (3) changes in the geothermal reservoir. The radon anomalies that were observed to follow the subsidence can be explained in terms of small perturbations of the geothermal reservoir (Figure 8). The absence of short-term anomalies preceding the subsidence suggests that none of the above three mechanisms contributes to intermittent changes of the radon content prior to subsidence.

Why no obvious evidence of intermittent magma degassing is observed in the radon content prior to subsidence could be related to the lack of a suitable transport mechanism. Possible precursory radon anomalies resulting from magma degassing would require the release of a noncondensing gas phase from the magma. Such a gas phase has to be transported up to the fumaroles in less than 16 days to contribute significantly to the radon emission, because the half-life of radon (Rn^{222}) is only 3.8 days. Hydrothermal convection as a transport mechanism over a distance of 3-4 km is probably too slow to play a significant role. Besides the hydrothermal convection, other possible mechanisms could contribute to transporting the original gas phase up to shallow crustal levels via small intrusions of magma or sudden opening of cracks. Several different variables in addition to radon emission, however, would be expected to indicate if intrusions or cracking played a significant role in transporting the gas phase. For instance, a shallow intrusion could lead to drastic changes in the fumarolic activity, as was observed in two exceptional cases. Opening of cracks that allowed gases to escape from the magma could result in some correlation between the radon emission and the local seismicity, which was not observed. The transition from uplift to subsidence appears to be related to the sudden opening of cracks, which permit the magma to flow laterally away from the chamber. If a separate gas phase has accumulated within the magma chamber, it will probably flow ahead of the magma laterally into the open cracks. Therefore it is possible that the magmatic gas phase will never reach the fumaroles, although the fumaroles are located directly above the magma chamber.

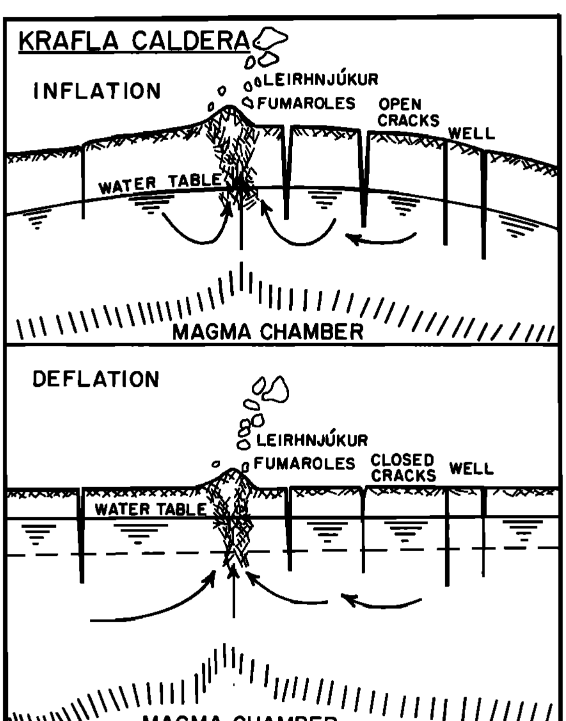

Fig. 8. Idealized model of the observed sequence of events. During inflation of magma chamber, caldera floor rises, cracks or fissures open, but radon emission and depth to water table remain constant. During deflation, caldera floor subsides, cracks close, and water table rises, resulting in increased radon emission from the fumaroles near Leirhnjukur.

Initially, the possible occurrence of dilatancy preceding the earthquakes in the caldera floor was considered to be capable of generating precursory radon anomalies. The absence of a correlation between the radon emission and the seismicity in the caldera suggests that the physical conditions at Krafla could be less favorable for the detection of such anomalies than elsewhere. The geothermal fluids within the caldera crust may not be capable of transporting the anomalies more than a few tenths of meters, since the local hydraulic gradient that depends on the local topography and the rock permeability is very shallow (A. Bjornsson, personal communication, 1980). Furthermore, the convective motion of geothermal fluids is probably impeded by the numerous dense intrusions revealed during the drilling of the deep geothermal wells [Stefansson, 1980]. In addition, the applied strain rate is on the order of 10^{-6} d^{-1}, which is 10^2 to 10^4 higher than in most other tectonic environments. In laboratory experiments, Sobolev et al. [1978] found that both the intensity and the size of the zone of precursory deformation associated with a dilatancy mechanism decrease with increasing strain or loading rate. Therefore, the possible anomalies associated with the seismicity during uplift are probably more localized and more difficult to detect than anomalies that are created at slow strain rates and under favorable hydraulic conditions.

Hauksson and Goddard [1981] noted that no correlation exists between the tectonic activity at Krafla and changes in the radon content of groundwater at stations located more than 30 km away. It therefore seems unlikely that the caldera as a whole could be regarded as an inclusion going through rapid inelastic deformation, with radon anomalies induced in the surrounding matrix, a mechanism applicable to some earthquakes [Hauksson, 1981].

Conclusions

The extensive set of radon and other types of data that have been gathered in the Krafla area during the last 3 years lead to the following conclusions:

Radon anomalies preceding subsidence and subsequent rifting and volcanism by weeks or days were not observed prior to the subsidence episodes of July 1978, November 1978, May 1979, March 1980, and October 1980.

Large radon anomalies, however, are observed regularly soon after the initiation of episodes of subsidence. The cause of the coepisodic anomalies appears to be a rise in the level of the geothermal water driven by crack closure, which results in a shorter transport time for radon from the water table (at depth of approximately 100 m) to fumaroles at the surface.

When using the water level data in conjunction with the radon data, the velocity of steam transport from the geothermal water at depth to the surface fumaroles is found to range from 26 m/d to 37 m/d.

Changes in radon emission also coincide with fluctuations in fumarolic activity and permanent changes in geothermal water level that occur during uplift periods. This coincidence supports the previous conclusion that changes in the transport path or time between the water table at depth and the surface fumaroles is the most likely mechanism for the changes in radon emission.

The lack of correlation between radon emission and the seismicity in the Krafla caldera may be attributable to unusually small zones of precursory deformation. Because the loading rate of the crust above the magma chamber during uplift is much higher than in most other tectonic environments, the zones of precursory deformation are expected to be unusually small. Furthermore, the shallow hydraulic gradient and an implied suppression of near surface fluid convection indicates that hydrothermal fluids within the caldera crust may not be capable of transporting anomalous radon more than a fraction of a meter.

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References

Asimov, M. S., Zh. S. Yerzhanov, K. Ye. Kalmurzaev, M. K. Kurbanov, G. A. Mavlyanov, S. Kh. Negmatullaev, I. L. Nersesov, and V. I. Ulomov, The state of earthquake prediction research in the Soviet Republics of Central Asia (in Russian), International Symposium on Earthquake Prediction, Rep. III-12, 20p, UNESCO, Paris, 1979.

Bjornsson, A., G. Johnsen, S. Sigurdsson, and G. Thorbergsson, Rifting of the plate boundary in north Iceland 1975-1978, J. Geophys. Res., 84, 3029-3038, 1979.

Chirkov, A. M., Radon as a possible criterion for predicting eruptions as observed at Karymsky volcano, Bull. Volcanol., 37, 126-131, 1975.

D'Amore, F., and C. Panichi, Evaluation of deep temperatures of hydrothermal systems by a new gas geothermometer, Geochim. Cosmochim. Acta, 44, 549-556, 1980.

D'Amore, F., and J. C. Sabroux, Signification de la presence de radon 222 dans les fluides geothermiques, Bull. Volcanol., 40-2, 106-115, 1977.

D'Amore, F., J. C. Sabroux, and P. Zettwoog, Determination of characteristics of steam reservoirs by radon-222 measurements in geothermal fluids, Pure Appl. Geophys., 117, 253-261, 1979.

Einarsson, P., S-wave shadows in the Krafla caldera in NE-Iceland, evidence for a magma chamber in the crust, Bull. Volcanol., 41-3, 1-9, 1978.

Gasparini, P., and M. S. M. Mantovani, Radon anomalies and volcanic eruptions, J. Volcanol. Geotherm. Res., 3, 325-341, 1978.

Gislason, G., H. 'Armannsson, and T. Hauksson, Krafla, temperature condition and gases in the geothermal reservoir (in Icelandic), Rep. OS-JHD-7846, Nat. Energy Authority, Reykjavik, Iceland, 1978.

Hauksson, E., Radon content of groundwater as an earthquake precursor: Evaluation of world-wide data and physical basis, J. Geophys. Res., 86, 1397, 1981.

Hauksson, E., and J. Goddard, Radon earthquake precursor studies in Icéland, J. Geophys. Res., 86, 7037, 1981.

Hauksson, E., A. Bjornsson, J. Beavan, and R. Bilham, Growth of large-scale ground fissure during rifting of the plate boundary in northern Iceland (abstract), Eos Trans. AGU, 60, 377, 1979.

Iwasaki, I., T. Ozawa, M. Yoshida, H. Kayda, and K. Yamaja, The change in the radon (Rn^{222}) and thoron (Rn^{220}) contents of volcanic gases in the Oowakidani district, Hakone volcano from 1960 to 1967, Bull. Volcanol. Soc. Jpn., 13(1), 21-31, 1968.

Iwasaki, I., T. Ozawa, M. Yoshida, and M. Kamada, Forecast of volcanic eruptions by chemical methods, Bull. Volcanol., 39(1), 91-103, 1975.

Oskarsson, N., Effect of magmatic activity on fumarole gas composition in the Namafjall-Krafla volcanic center, N-Iceland, Rep. 7803, Nord. Volcanol. Inst., Univ. of Iceland, Reykjavik, Iceland, 1978.

Saemundsson, K., Evolution of the axial rifting zone in Northern Iceland and the Tjornes Fracture Zone, Geol. Soc. Am. Bull., 85, 495-504, April 1974.

Saemundsson, K., Geological map of Iceland, sheet 7, NE-Iceland, Icelandic Geod. Surv. and Museum of Nat. Hist., Reyhjavik, Iceland, 1977.

Saemundsson, K., Fissure swarms and central volcanoes of the neovolcanic zones of Iceland, Geol. J. Spec. Issue No. 10, 415-432, 1978.

Sobolev, G., H. Spetzler, and B. Salov, Precursors to failure in rocks while undergoing anelastic deformation, J. Geophys. Res., 83, 1775-1784, 1978.

Stefansson, V., The Krafla geothermal field, northeast Iceland, in Geothermal Resources, edited by L. Ryback and P. Muffler, John Wiley, New York, 1980.

Tryggvason, E., Subsidence events in the Krafla area, North Iceland, 1975-1979, J. Geophys., 47, 141-153, 1980.

Wakita, H., Earthquake prediction and geochemical studies in China, Chin. Geophys., 1(2), 443-457, 1978.

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